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APPLICATION NUMBER: ***60/555,109***
FILING DATE: ***March 22, 2004***
RELATED PCT APPLICATION NUMBER: ***PCT/US05/09383***

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This is a request for filing a PROVISIONAL APPLICATION FOR PATENT under 37 CFR 1.53(c).

17510 U.S. PTO 60/555100

032204

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☐ *Additional inventors are being named on the ____ separately numbered sheets attached hereto*

TITLE OF THE INVENTION (280 characters max)

HIGH SENSITIVITY METAL-SEMICONDUCTOR-METAL PHOTODETECTOR

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ENCLOSED APPLICATION PARTS *(check all that apply)*

☒ Specification *Number of Pages* 13

☒ Drawing(s) *Number of Sheets* 8

☐ Application Data Sheet. See 37 CFR 1.76

☐ CD(s), Number

☐ Other (specify)

METHOD OF PAYMENT OF FILING FEES FOR THIS PROVISIONAL APPLICATION FOR PATENT *(check one)*

☒ Applicant claims small entity status. See 37 CFR 1.27.

☒ A check or money order is enclosed to cover the filing fees

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FILING FEE AMOUNT ($): $80.00

The invention was made by an agency of the United States Government or under a contract with an agency of the United States Government.

☐ No.

☐ Yes, the name of the U.S. Government agency and the Government contract number are: ______

Respectfully submitted,

SIGNATURE Betsy Kingsbury Dowd

Date 3/22/04

TYPED or PRINTED NAME Betsy Kingsbury Dowd

REGISTRATION NO. 52,830
(if appropriate)

Docket Number: 1038-12P

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USE ONLY FOR FILING A PROVISIONAL APPLICATION FOR PATENT

HIGH SENSITIVITY METAL-SEMICONDUCTOR-METAL PHOTODETECTOR

Field of the Invention

[0001] The invention relates to the field of high sensitivity photoconductors and more particularly to high speed, high sensitivity metal-semiconductor-metal photodetectors and methods of fabricating the same.

Background

[0002] In prior art metal-semiconductor-metal (MSM) detectors, as light of an energy sufficiently larger than the bandgap of the semiconductor is incident on the structure, some of the incident light impinges on the semiconductor between the electrodes and excites charge carriers, i.e. electrons and holes, in the semiconductor. The electrons are swept away by the applied voltage and electric field toward positively charged electrodes. The holes are swept in the opposite direction towards the negatively charged electrodes. The charge carriers are collected at the electrodes and produce a measurable electric current.

[0003] The speed of the MSM device is generally partially limited by the time necessary for charges to be swept to the electrodes. One method to increase the speed of these MSM devices has been to reduce the spacing between adjacent electrodes. The reduced spacing shortens the distance the carriers have to travel to the electrodes, therefore decreasing the transit time. The decreased transit time results in increased speed of the device. This increased speed is an advantage of MSM devices over other types of detectors. By reducing the spacing, however, a large percentage of the surface of the device is covered with metallic reflective electrodes that reflect the incident light, resulting in lower sensitivity. Consequently, light sensitivity is sacrificed for high speed in typical MSM devices.

[0004] There is a need, therefore, lacking in the prior art, for MSM devices having both fast response times and high sensitivity.

Brief Description of the Drawings

[0005] FIG. 1 is a cross-section of a side view of an embodiment of an MSM detector formed in accordance with the present invention.

[0006] FIG. 2 is a top view of an electrode structure of an embodiment of an MSM detector formed in accordance with the present invention.

[0007] FIG. 3 is a side view of a preferred embodiment of an MSM detector formed in accordance with the present invention.

[0008] FIG. 4 is a plot of capacitance of a typical prior art MSM device.

[0009] FIG. 5 is a dispersion curve of prior art MSM devices.

[0010] FIG. 6 is a plot of an electromagnetic field profile of a prior art MSM device.

[0011] FIG. 7 is a dispersion curve of an MSM detector formed in accordance with the present invention.

[0012] FIG. 8 is a plot of the electromagnetic field profile of an MSM detector formed in accordance with the present invention.

Detailed Description

[0013] Referring to FIG. 1, an optical detector 10 of the present invention includes a multiplicity of electrodes 12 spaced in a substantially regular pattern. The electrodes 12 are adapted to resonantly couple between an external optical wave 14 to be detected and a local wave, i.e., a surface plasmon wave 15. The surface plasmon wave 15 includes a component of momentum oriented substantially perpendicular to a detector surface 16 of the detector 10.

[0014] The detector surface 16 of the detector 10 is a substantially planar surface exposed to the external optical wave 14, which is not covered by the electrodes 12.

[0015] In addition, a structure is associated with the multiplicity of electrodes 12, wherein the structure and the multiplicity of electrodes 12 support the component of momentum of the surface plasmon wave 15. The momentum is oriented substantially perpendicular to the

detector surface 16. A sensor (not shown) is connected to the electrodes 12 for sensing an electrical quantity.

[0016] The optical detector 10 further includes a substrate 22 in superposed relationship with the multiplicity of electrodes 12. The substrate 22 preferably includes a semiconductor material.

[0017] In one embodiment, the detector surface 16 is a surface of the substrate 22.

[0018] In another embodiment, a layer of transmissive optical material is deposited on the substrate 22 and forms the detector surface 16.

[0019] The detector 10 of the present invention is further advantageously characterized by an aspect ratio sufficient to support the substantially perpendicular surface plasmon modes 15. The aspect ratio is defined as a ratio of a height 18 of the electrodes 12 to a spacing 20 between adjacent electrodes 12.

[0020] In one embodiment, the aspect ratio is preferably at least about 3 in order to support the substantially perpendicular components of momentum of the surface plasmon wave.

[0021] In another embodiment, the aspect ratio is preferably less than about 16.

[0022] In a preferred embodiment, the aspect ratio is substantially in a range of at least about 4 to less than about 10.

[0023] In another embodiment, the aspect ratio is preferably substantially in a range greater than about 10 to less than about 15.

[0024] In another embodiment, the aspect ratio is preferably substantially in a range of at least about 7 to less than about 12.

[0025] The substrate 22 of the present invention preferably comprises a semiconductor. The substrate 22 may be comprised of any semiconductor material, including III-IV semiconductors, Silicon (Si), and ternary compound semiconductors, including, for example, Gallium Indium Arsenide (GaInAs) and Gallium Aluminum Arsenide (GaAlAs).

[0026] The electrodes 12 of the present invention preferably comprise a metal. The electrodes 12 are further characterized by having a potential difference between adjacent electrodes.

[0027] Further, the potential difference between adjacent electrodes is preferably achieved by maintaining a positive voltage on a first electrode 24, and a negative voltage on a second electrode 26, the first 24 and second 26 electrodes being adjacent electrodes.

[0028] In one embodiment, the electrodes 12 comprise a metal and the substrate 22 comprises a semiconductor material. This arrangement of metal electrodes and semiconductor is commonly referred to as a metal-semiconductor-metal (MSM) detector.

[0029] The electrodes 12 may be of any shape and in any geometrical pattern for which coupling of the substantially perpendicular surface plasmon modes can occur.

[0030] In the embodiment shown in FIG. 1, the electrodes 12 are substantially rectangular in shape and substantially perpendicular to the detector surface 16.

[0031] In one embodiment, an interface between the electrodes 12 and the substrate 22 is characterized as a substantially straight edge.

[0032] In another embodiment, the interface between the electrodes 12 and the substrate 22 is characterized as substantially curved or sloped. The substantially sloped interface that can occur in manufacturing does not affect the coupling of surface plasmon modes 15 substantially perpendicular to the detector surface 16, but may shift the resonance energy of the modes 15 and must be taken into account in optimizing parameters of a device formed in accordance with the present invention.

[0033] In one embodiment shown in FIG. 2, the electrodes 12 are preferably interdigitated metal electrodes. As shown, the interdigitated electrodes 12 include protruding fingers, which form back-to-back Schottky contacts when deposited on the surface of a semiconductor substrate 22. The electrodes 12 of the present invention are arranged in a preferred geometric structure. The preferred structure optimizes the production of surface plasmon modes oriented substantially perpendicular to the detector surface 16 of the device, at a particular wavelength, angle of incidence, and polarization of the incident light. When the light satisfies these parameters, it is largely transmitted through the array of metallic

contacts 12 and into the semiconductor 22. The light which channels into the semiconductive substrate 22 excites electron-hole pairs which are then collected by the contacts 12, preferably registering a photocurrent. Due to the surface plasmon coupling, the amount of light collected is larger than that which is directly incident on the area of the semiconductor material not covered by the electrodes 12.

[0034] Surface plasmons are electromagnetic excitations at the surface of a metal, which, once excited, can transfer part of their energy into an adjoining surface, in this case, the semiconductor. The surface plasmons, therefore, advantageously increase the efficiency of a photodetector. Prior art devices have applied the concept of surface plasmons to flat or low profile electrode geometries, because it was seen that the surface plasmons in the plane of, and parallel to, the detector enhanced the amount of light coupled into the semiconductor.

[0035] Referring to FIG. 1 through FIG. 2, the MSM detector of the present invention exploits the surface plasmons oriented substantially perpendicular to the detector surface 16 to enhance the efficiency of transmission of light. The enhanced transmission is achieved by using a high aspect ratio electrode structure. The enhanced transmission allows for smaller spacing 20 between adjacent fingers of the electrodes 12 and larger height 18. The larger electrode height 18 produces less resistance in the fingers of the electrodes 12, producing a higher speed device without significantly reducing the light sensitivity of the device. The smaller spacing 20 decreases the transit time of the photogenerated carriers, thus also increasing the speed of the device without significantly reducing the light sensitivity of the device.

[0036] The spacing of an MSM detector formed in accordance with the present invention is preferably not less than about 20 nanometers (nm).

[0037] In still another embodiment of an MSM device formed in accordance with the present invention, a particular preferred geometry and aspect ratio of the contacts, e.g. the fingers, are determined by a preferred wavelength, polarization, and angle of incidence sensitivity desired. Referring still to FIG. 1 and FIG. 2, the optimal height 18 and aspect ratio is preferably determined, in part, by a preferred range of optical wavelength sensitivity of the optical detector 10 formed in accordance with the present invention. Generally, as the contact or finger height 18 increases, surface plasmon energy decreases, and the corresponding wavelength of the surface plasmon resonance increases. The height 18 is

preferably chosen so that the surface plasmon resonance wavelength corresponds to a wavelength at peak responsivity of the semiconductor 22, the detector 10 being optimized for detection of light in the range of peak spectral responsivity of the semiconductor material.

[0038] In one embodiment, a minimum height of the electrical contacts or fingers of the electrodes of a detector of the present invention is about 50 nm.

[0039] In another embodiment, a maximum height of the electrical contacts or fingers of the electrodes of a detector of the present invention is about 1500 nm.

[0040] In yet another embodiment, a height of the electrical contacts or fingers of the electrodes of a detector of the present invention is substantially within a range of about 100 nm to about 750 nm.

[0041] The dependence of polarization and angle of incidence on the amount of incident light, centered at a particular wavelength, which is transmitted through a linear stepped profile or grating structure is well-known to those skilled in the art. The substantially regular pattern of the electrodes of the present invention represents a grating-like structure. The geometry (in particular, the spacing 20 and electrode pitch) of the electrode structure of the present invention, therefore, is preferably additionally optimized to enhance a preferred angle of incidence of the incident light at a particular wavelength to be detected. As is well-known to those skilled in the art, the amount of a linearly polarized light which will be transmitted is determined largely by the orientation of the incident polarized wave relative to the orientation of the electrode structure.

[0042] The device of the present invention, therefore, preferably optimizes the electrode spacing, pitch, and orientation to exploit the resonant coupling effect, well-known to those skilled in the art, provided by the substantially regular electrode structure (i.e., an electrode grating). These parameters are optimized in accordance with the preferred wavelength, polarization, and angle of incidence sensitivity of the detector formed in accordance with the present invention. The height of the electrode contacts is further optimized to reduce resistivity for increased speed and simultaneously, to enhance transmission of light within the preferred wavelength sensitivity range by resonant coupling with the substantially perpendicular surface plasmon modes.

[0043] In yet another embodiment, an MSM device of the present invention further includes a second multiplicity of electrodes spaced in a substantially regular pattern and positioned in superposed relationship with the substrate and the multiplicity of electrodes. The second multiplicity of electrodes is rotated at an angle relative to the orientation of fingers of the first electrodes and in the plane of the detector surface. Preferably, the second multiplicity of electrodes is rotated at an angle of about 90° to the fingers of the first electrodes.

[0044] The second multiplicity of electrodes is also adapted to support a surface plasmon wave having a component of momentum oriented substantially perpendicular to the detector surface. The MSM device of this embodiment will preferably resonantly couple at least orthogonal linear polarization components of unpolarized light incident on the device, therefore, advantageously enhancing detection of unpolarized light.

[0045] By exploiting the substantially perpendicular components of the momentum, in contrast to the prior art, both high light sensitivity and a fast response time are achieved at the preferred wavelength, polarization, and angle of incidence. The high aspect ratio structure is specifically adapted to support the component of the surface plasmons substantially perpendicular to the detector surface 16 of the detector 10. The high aspect ratio of the MSM device 10 of the present invention is preferably not less than about 3 and not greater than about 16. A preferred embodiment of the MSM device 10 of the present invention includes an aspect ratio substantially in a range greater than about 10 and less than about 15.

[0046] Referring to FIG. 3, a preferred embodiment 30 of an MSM detector formed in accordance with the present invention includes a second semiconductor material 28 positioned in the deep spacing 20 between adjacent fingers of the electrodes 12. The second semiconductor 28 preferably comprises the same semiconductor material as the substrate 22. In this embodiment, the absorbing semiconductor material 28 is preferably in the location of the amplified electromagnetic fields caused by the surface plasmons, and therefore, the device 30 shown in FIG. 3 will have a significantly higher sensitivity than existing devices.

[0047] The speed of response of a photodetector is typically partially limited by an intrinsic response time, defined as the duration in time necessary for the device to return to equilibrium after being exposed to light. In other words, when a light pulse penetrates the semiconductor material of a typical MSM detector, it generates hole pairs which are swept away from the semiconductor and toward the electrodes. The holes travel toward a

negatively charged electrode, while the electrons travel toward a positively charged electrode. The photogenerated electrons and holes either reach the respective electrode and leave the semiconductor material or recombine with each other. The period of time it takes for the electron and hole concentrations to return to their equilibrium conditions is the intrinsic response time. The intrinsic response time is typically limited either by the transit time of electrons and holes between the electrodes or carrier recombination time.

[0048] The speed of response of prior art MSM devices, therefore, has been increased by reducing the spacing between adjacent electrodes. The speed of response, however, is also partially limited by the resistance and capacitance of the electrodes, the speed being inversely proportional to the product of the resistance and capacitance of the electrodes. It has been recognized in the prior art, that the capacitance and the transit time can both be advantageously reduced by reducing both the spacing between adjacent electrodes and reducing the width of the electrodes. In so doing, however, the resistance of the device is increased, hence reducing the speed of the device.

[0049] In the MSM device of the present invention, the intrinsic response time is reduced and speed of response of the device is preferably increased by reducing the spacing between adjacent electrodes or electrode fingers to increase the speed (by reducing transit time), while increasing the height 18 and the aspect ratio to reduce the resistance of the device 10.

[0050] Referring again to FIG. 1 and FIG. 2, the speed of response of the MSM device 10 of the present invention is proportional to the inverse of the product of the resistance and capacitance of the so-called fingers 32 of the interdigitated electrodes 12. The capacitance per finger length C_o is defined by equation (1) as follows:

$$C_o = \frac{\varepsilon_o(1+\varepsilon_r)K(k)}{K(k')} \tag{1}$$

where C_o is the capacitance per finger length, ε_o is the permittivity of free space, ε_r is the dielectric constant of the semiconductor and $K(k)$ and $K(k')$ are elliptical integrals defined by the following equations:

$$K(k)=\int_0^{\pi/2}\frac{d\phi}{\sqrt{1-k^2\sin^2\phi}} \qquad (2)$$

$$k'=\sqrt{1-k^2} \qquad \text{and} \qquad k=\tan^2\frac{\pi w}{4p} \qquad (3).$$

In these equations, w is the electrode width and p is the electrode pitch.

[0051] In addition, the total capacitance, C, of the device 10 is inversely proportional to the pitch, p, in accordance with the following equation:

$$C = C_o \times A_{device}/p \qquad (4),$$

where $A_{device} = l_{device} \times w_{device}$ is the total area of the device, l_{device} and w_{device} being the length and width of the device respectively.

[0052] Applying equations (1) through (4), a plot 32 of the capacitance per finger length, C_o, as a function of the ratio of finger width to pitch 36 is plotted in FIG. 4. From FIG. 4, it is seen that as the spacing 20 between the electrode fingers 12 decreases for a fixed electrode pitch p (or equivalently, when the electrode width w increases relative to the pitch), the overall capacitance C increases, thus limiting the speed of the device. Reducing the resistance by increasing the thickness 18 (see FIG. 1) of the fingers of the electrodes 12 offsets this increase in capacitance, allowing a reduction in the spacing 20 of the fingers 12 (see FIG. 2) to increase speed by reducing transit time of the electrons.

[0053] The structure of a device formed in accordance with the present invention, therefore, comprises a high aspect ratio, and advantageously supports surface plasmon resonance modes substantially perpendicular to a detector surface. This structure enhances light channeling into a semiconductive substrate. Simultaneously, the high aspect ratio geometry offsets the increase in capacitance caused by preferably reducing the electrode spacing to increase the speed of response of the device. Further, a height of the electrodes is preferably optimized

for a preferred wavelength sensitivity, and an optimum aspect ratio and preferred geometry of the device are found by considering effects of height and spacing on speed, as well as on the preferred wavelength, angle of incidence, and polarization sensitivity desired.

EXAMPLES

[0054] Numerical models have been developed to model the effect of surface plasmon resonance in prior art devices and in MSM devices formed in accordance with the present invention. Results are provided herein.

[0055] FIG. 5 shows a dispersion curve 40 of prior art devices. Energy is plotted as a function of the wavevector for all possible radiating light modes (shaded area 42), for surface plasmons on a flat surface 44 and for surface plasmon modes on a slightly periodically modulated metal surface 46. The line 44 describing the surface plasmon modes on a flat surface never lies in the shaded area 42, indicating that these modes can not interact with light. The altered modes are in the shaded area 42 and can interact with light. These are the modes with momentum component parallel to the device surface, representative of prior art devices.

[0056] FIG. 6 represents the electromagnetic field profile of a typical surface plasmon mode 50 with momentum K_{sp} 52 parallel to a surface 54 having a small periodically modulated air/metal interface. The field is amplified at the interface 54 causing some enhanced detector sensitivity.

[0057] Referring to FIG. 7, the dispersion curve 60 of high aspect ratio MSM detectors of the present invention differs markedly from that of the prior art MSM detectors as can be seen by comparison with FIG. 5. The high aspect ratio MSM device described by FIG. 7 comprises 250 nm thick aluminum contacts spaced 250 nm apart and with 30 nm spacing in between the contacts, corresponding to an aspect ratio greater than 8.

[0058] FIG. 7 is a graph of the reflectivity of light incident on the structure as a function of energy on the y-axis and normalized in-plane momentum (i.e., momentum parallel to the surface of the device) on the x-axis. A minimum in the reflectivity curves indicates the

existence of a surface plasmon mode. In Fig. 7, these minima are seen as shaded dark lines or areas.

[0059] The surface plasmons modes shown in FIG. 7 near and along the $k_x/(K/2) = 0$ (i.e. the y-axis) correspond to surface plasmon modes with close to zero in-plane momentum and nonzero momentum substantially perpendicular to the surface of the device. The light that excites or produces these modes is substantially normally incident light (i.e., light that has a zero angle of incidence), a common angle of incidence encountered in applications of an MSM device.

[0060] In this example, the detector is optimized for an energy centered at about 2.5 eV, corresponding to enhanced transmission of incident light with an optical wavelength of about 500 nm.

[0061] FIG. 8 is a plot of the electromagnetic field profile 70 for the high aspect ratio MSM detector described by FIG. 7.

What is claimed is:

1. In an optical detector for sensing the strength of an external optical wave comprising:

a multiplicity of electrodes spaced in a substantially regular pattern, the multiplicity of electrodes adapted to resonantly couple between the external optical wave and a local optical wave and to allow a potential difference between adjacent electrodes, wherein the multiplicity of electrodes comprise a metal;

a structure associated with the multiplicity of electrodes, wherein the structure and the multiplicity of electrodes support the local wave; and

a sensor connected to the multiplicity of electrodes for sensing an electrical quantity,

the improvement comprising:

a substrate, the multiplicity of electrodes being in superposed relationship with the substrate; and

an aspect ratio of a height of the multiplicity of electrodes to a spacing between adjacent electrodes, the aspect ratio being at least 3;

wherein the substrate comprises a semiconductor, and further

wherein the local wave is a surface plasmon wave having a component of momentum oriented substantially perpendicular to a detector surface.

2. The optical detector of Claim 1, wherein the spacing is at least about 20 nanometers.

3. The optical detector of Claim 1, wherein the aspect ratio is substantially in a range greater than about 4 and less than about 16.

4. The optical detector of Claim 1, wherein the aspect ratio is substantially in a range greater than about 10 and less than about 15.

5. The optical detector of Claim 1, further comprising:

a second multiplicity of electrodes spaced in a substantially regular pattern rotated 90° in the plane of the detector surface, the second multiplicity of electrodes being in superposed relationship with the multiplicity of electrodes and the substrate, wherein the second multiplicity of electrodes are adapted to resonantly couple between the external optical wave

and the surface plasmon wave, the surface plasmon wave having a component of momentum oriented substantially perpendicular to the detector surface.

6. The optical detector of Claim 1, further comprising a semiconductor layer substantially filling the spacing between adjacent electrodes.

7. The optical detector of Claim 1, wherein the height of the multiplicity of electrodes is at least about 50 nanometers.

8. The optical detector of Claim 1, wherein the height of the multiplicity of electrodes is substantially in a range of about 50 nanometers to about 1500 nanometers.

9. The optical detector of Claim 1, wherein the height of the multiplicity of electrodes is substantially in a range of about 100 nanometers to about 750 nanometers.

FIG. 1

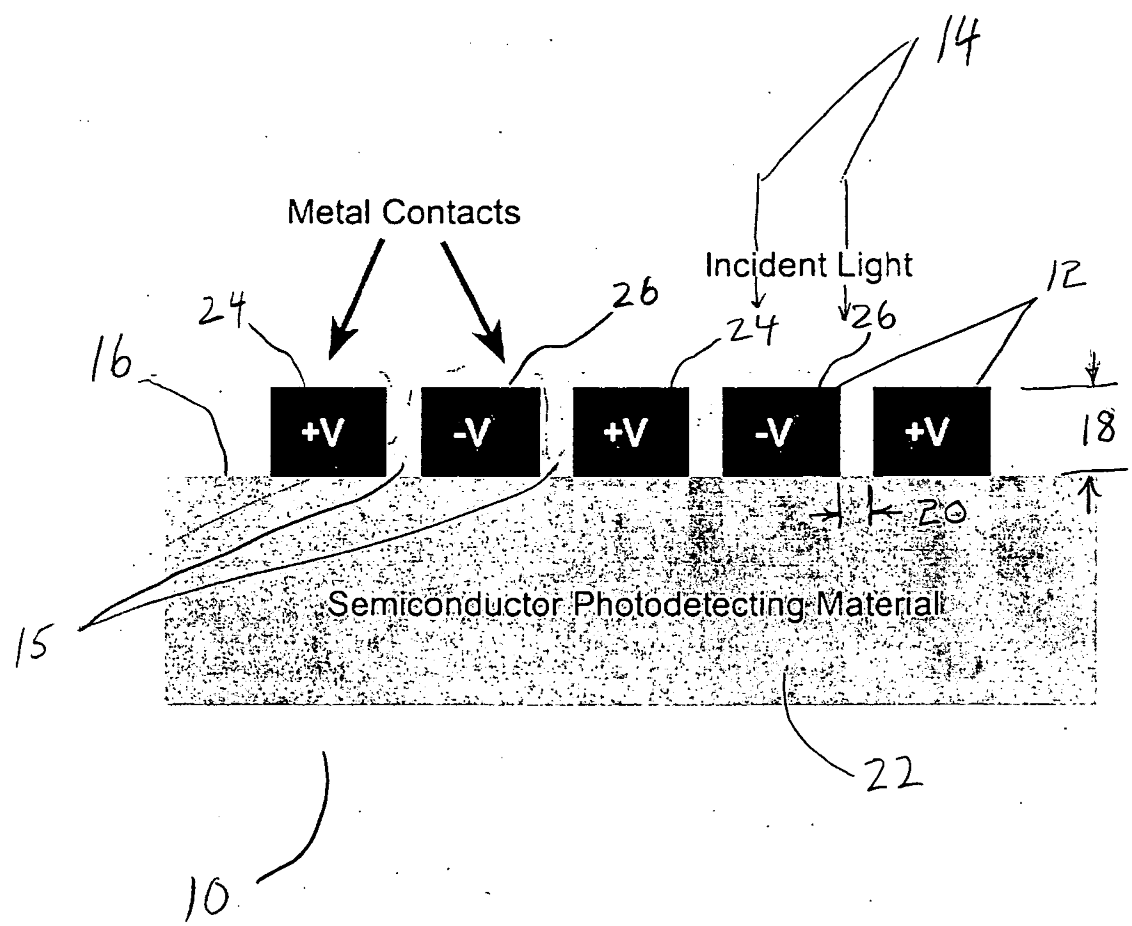
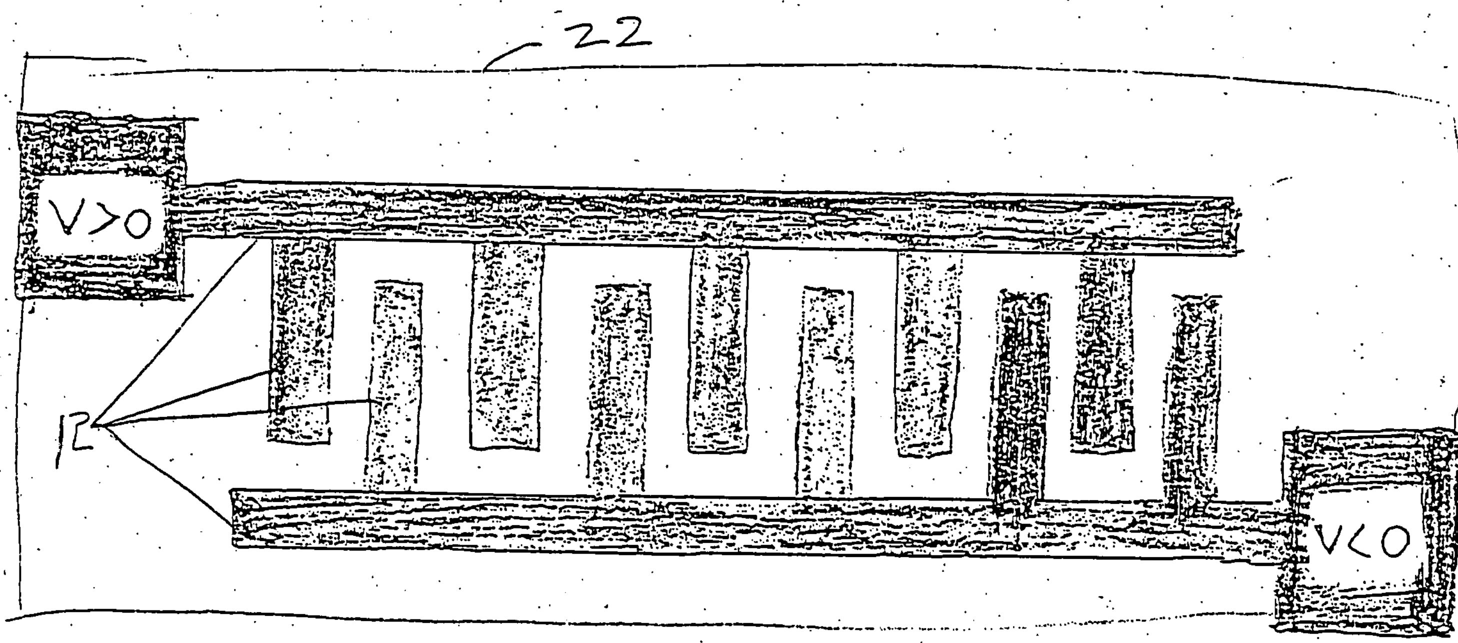

14
Metal Contacts
Incident Light
12
24
26
24
26
16
+V
-V
+V
-V
+V
18
20
Semiconductor Photodetecting Material
15
22
10

FIG. 2



Top view showing interdigitated metallic contacts

FIG. 3

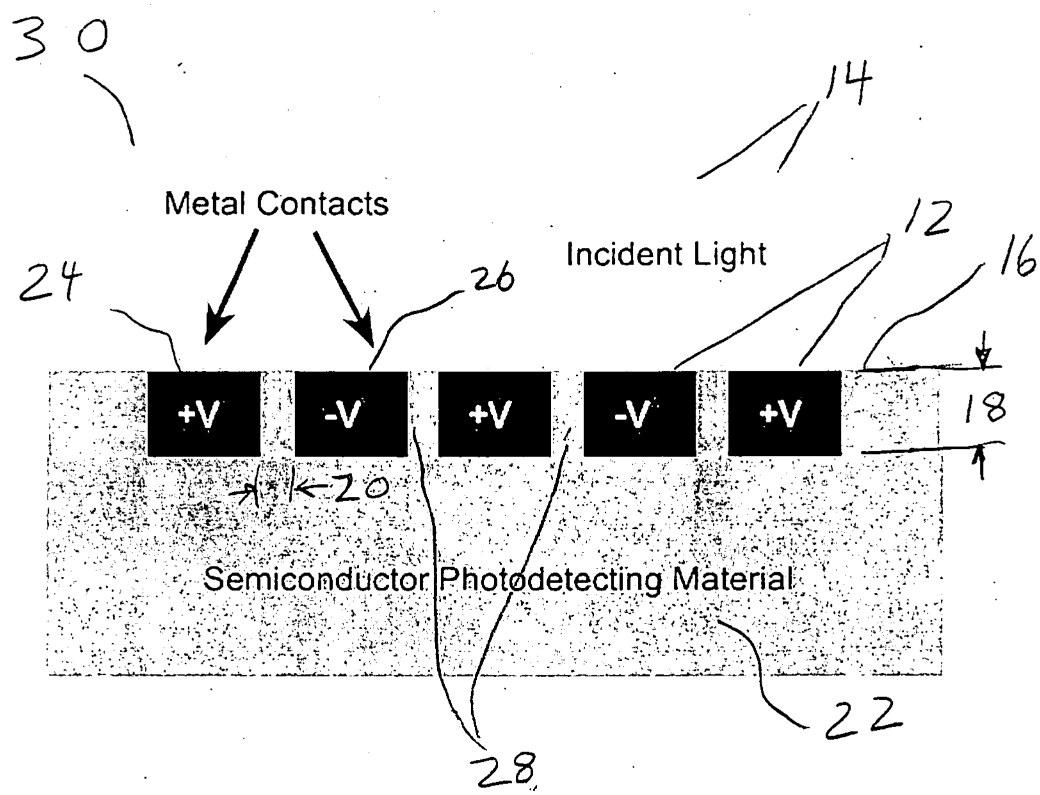

30
14
Metal Contacts
Incident Light
12
16
24
26
+V
-V
+V
-V
+V
18
20
Semiconductor Photodetecting Material
22
28

FIG. 4

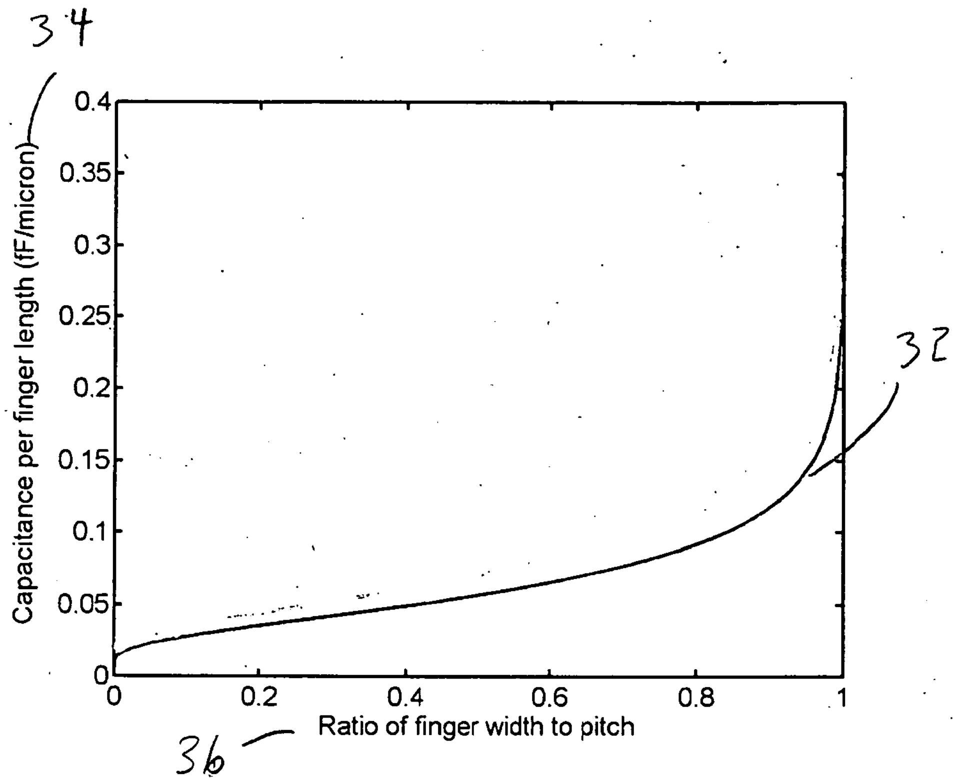

34
32
36
Capacitance per finger length (fF/micron)
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0.2
0.4
0.6
0.8
1
Ratio of finger width to pitch

FIG. 5

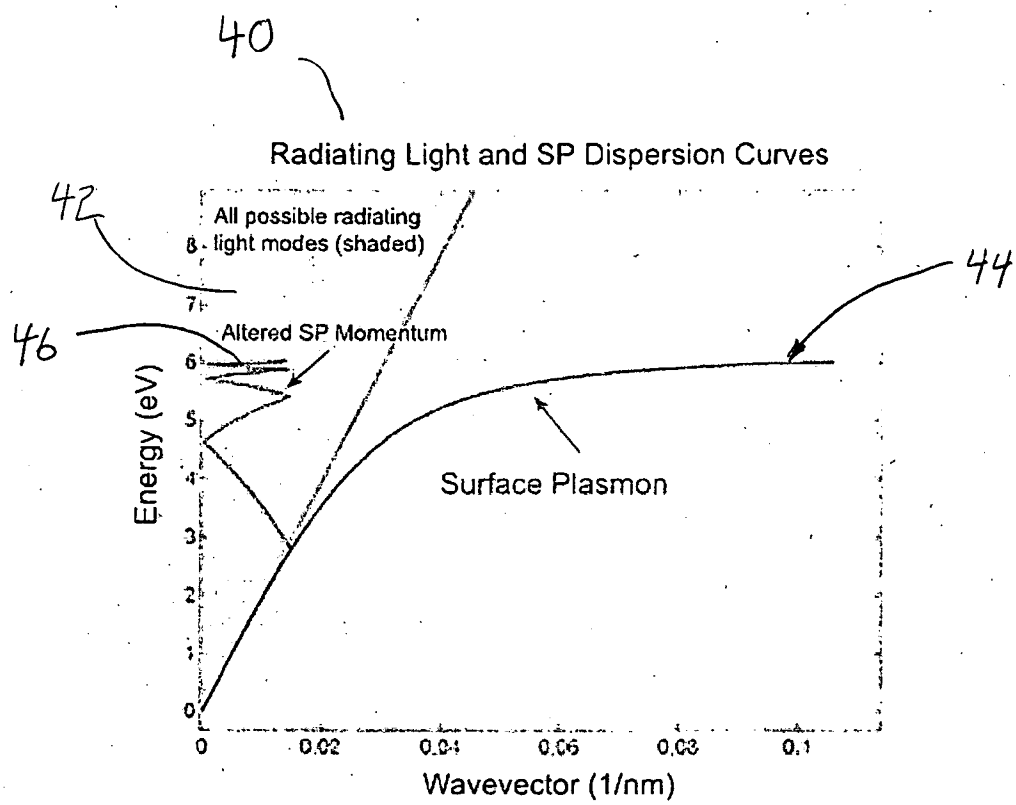

40
Radiating Light and SP Dispersion Curves
42
All possible radiating light modes (shaded)
46
Altered SP Momentum
44
Surface Plasmon
Energy (eV)
Wavevector (1/nm)
0
0.02
0.04
0.06
0.08
0.1
1
2
3
4
5
6
7
8

FIG. 6

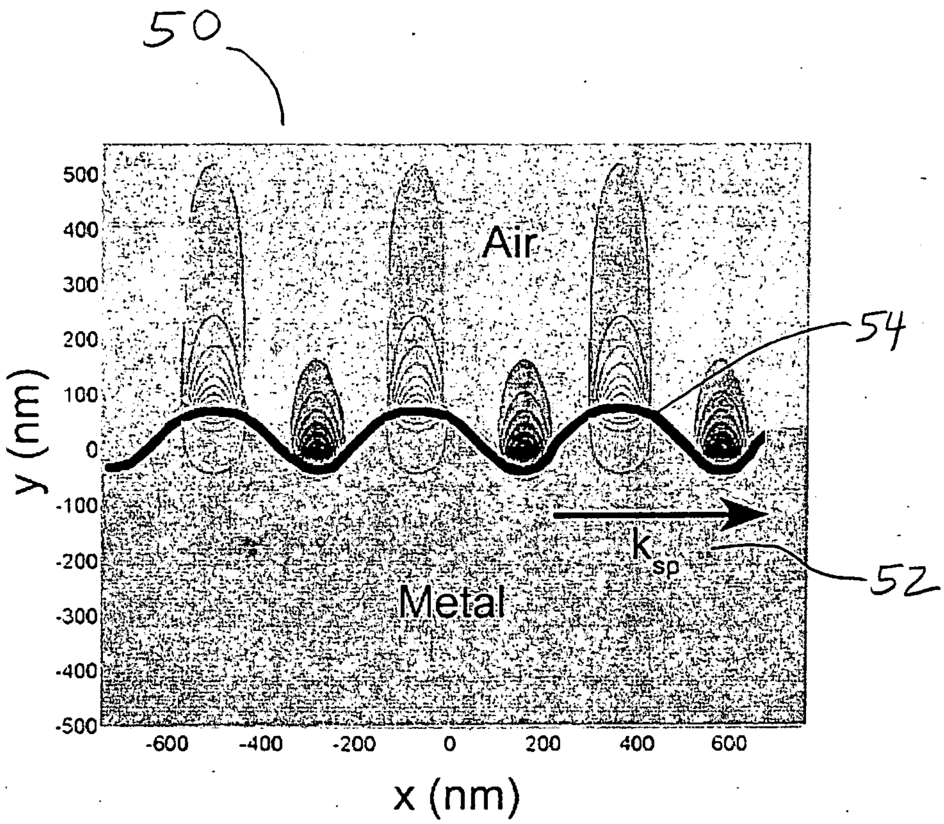

50
54
52
Air
Metal
k_{sp}
y (nm)
x (nm)
500
400
300
200
100
0
-100
-200
-300
-400
-500
-600
-400
-200
0
200
400
600

FIG. 7

60

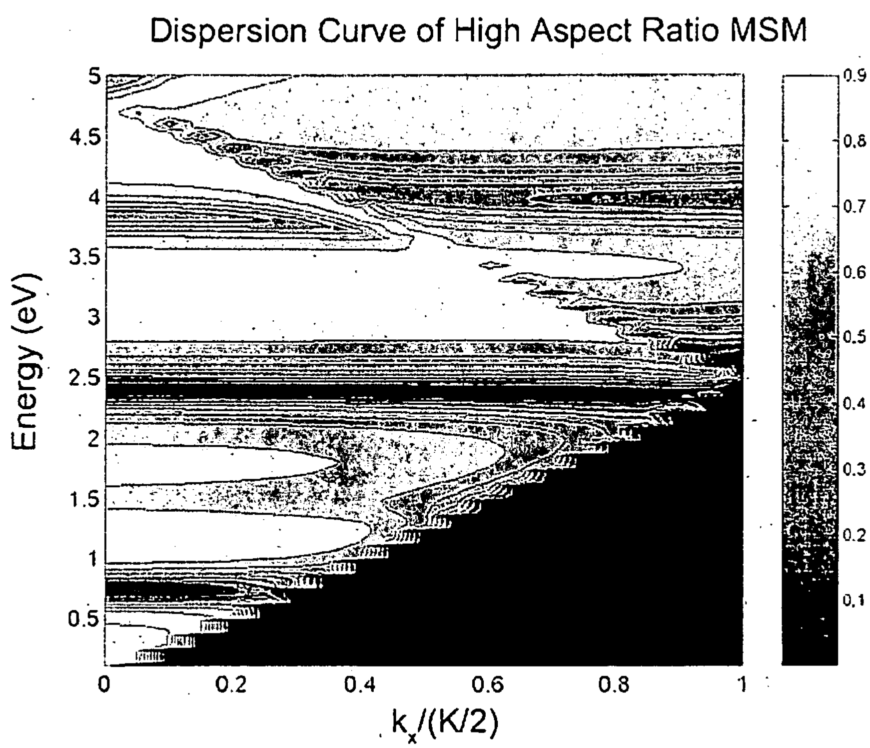
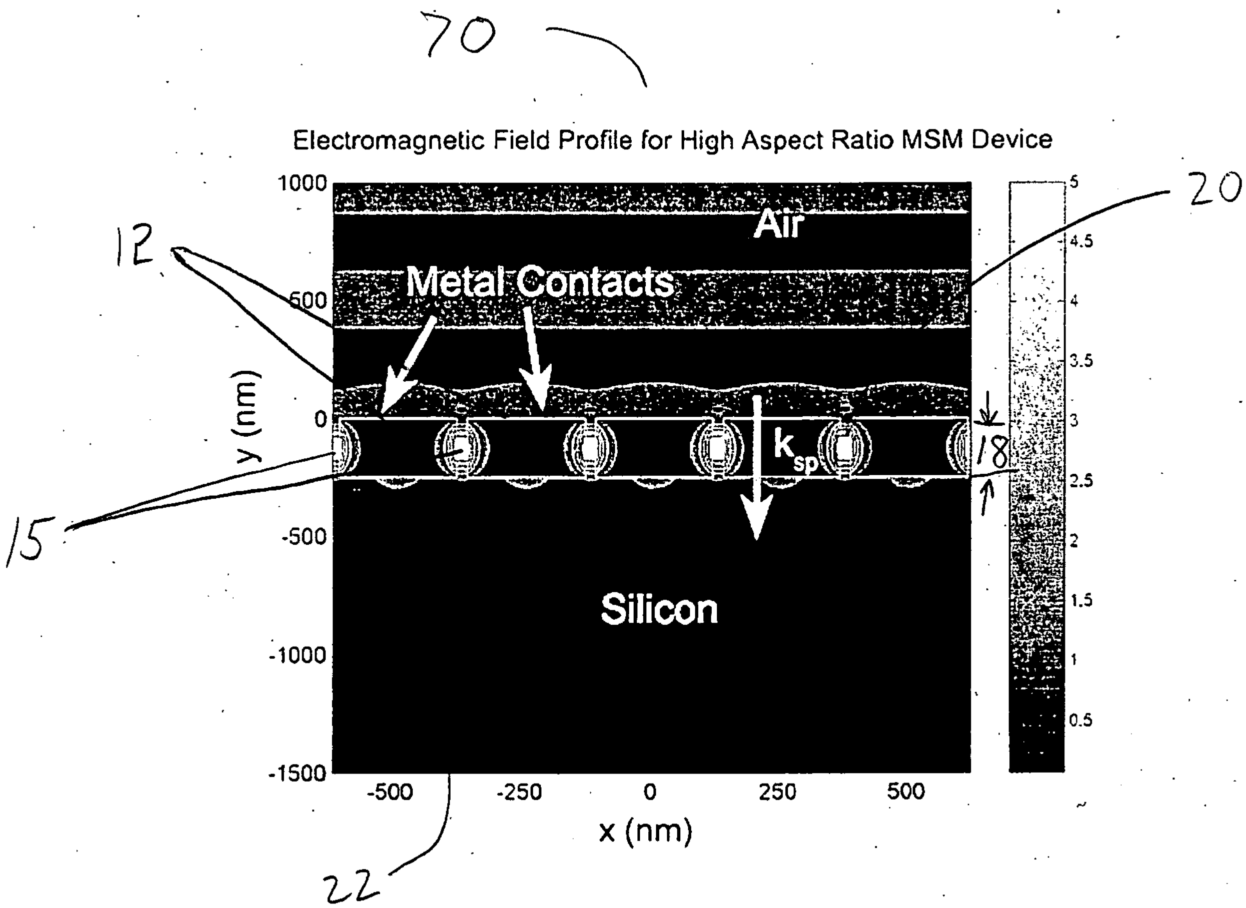

Dispersion Curve of High Aspect Ratio MSM
Energy (eV)
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0.2
0.4
0.6
0.8
1
$k_x/(K/2)$
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1

FIG. 8


70
Electromagnetic Field Profile for High Aspect Ratio MSM Device
Air
Metal Contacts
Silicon
k_{sp}
y (nm)
x (nm)
1000
500
0
-500
-1000
-1500
-500
-250
0
250
500
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
12
20
15
18
22